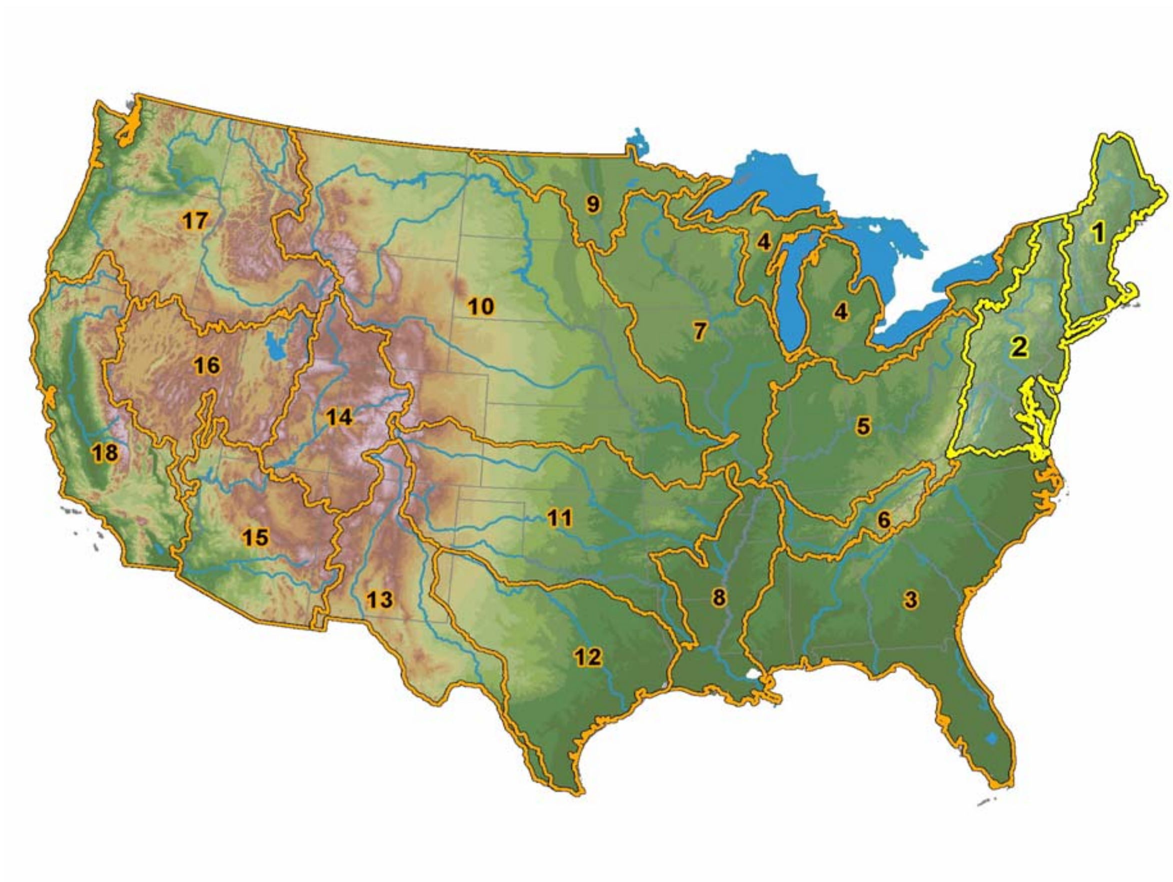
DOE/ID-11077
April 2003

Low Head/Low Power Hydropower Resource Assessment of the North Atlantic and Middle Atlantic Hydrologic Regions



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Low Head/Low Power Hydropower Resource Assessment of the North Atlantic and Middle Atlantic Hydrologic Regions

Douglas G. Hall, INEEL
Gregory R. Carroll, BNI
Shane J. Cherry, INEEL
Randy D. Lee, INEEL
Garold L. Sommers, INEEL

IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Published April 2003

Prepared for the
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Wind and Hydropower Technologies
Idaho Operations Office

ABSTRACT

An analytical assessment of the hydropower potential of the combined area of the North Atlantic and Middle Atlantic Hydrologic Regions was performed using state-of-the-art digital elevation models and geographic information system tools. The principal focus of the study was the amount of low head (less than 30 ft)/low power (less than 1 MW) potential in the study area and the fractions of this potential that corresponded to the operating envelopes of three classes of hydropower technologies: conventional turbines, unconventional systems, and microhydro (less than 100 kW). To obtain these estimates, the hydropower potential of all the stream segments in the study area, which averaged 2 miles in length, were calculated. These calculations were performed using hydrography and hydraulic heads that were obtained from the U.S. Geological Survey's Elevation Derivatives for National Applications dataset and stream flow predictions from regression equations developed specifically for each of the hydrologic regions in the study area. Stream segments excluded from development and developed hydropower in the area were accounted for to produce estimates of available total hydropower potential. The total available hydropower potential in the study area was subdivided into high power (1 MW or more), high head (30 ft or more)/low power, and low head/low power total potentials. The sites of available low head/low power potentials corresponding to the three classes of technologies and high head/low power potential are displayed on maps of the area.

SUMMARY

The U.S. Department of Energy (DOE) has had an ongoing interest in assessing the hydropower potential of the United States. Previous assessments have focused on potential projects that have a capacity of 1 MW and above (Connor et al. 1998). These assessments were also based on previously identified sites with a recognized, although varying, level of development potential. In FY 2000, DOE initiated planning for an assessment of hydropower potential for low head (less than 30 feet) and low power (less than 1 MW) resources.

The Idaho National Engineering and Environmental Laboratory in conjunction with the U.S. Geological Survey recently completed the third in a planned series of low head/low power hydropower resource assessments, which in combination will result in an assessment of the entire conterminous U.S. The study area for this assessment was the combined area of the North Atlantic (HUC 1) and Middle Atlantic (HUC 2) Hydrologic Regions.

The method used in this study uses state-of-the-art digital elevation models and geographic information system (GIS) tools to assess the hydropower potential of every stream segment within a chosen study area. Summing the estimated hydropower potential of all the stream segments in the area provided an estimate of the total hydropower in the area. Stream segments that had power potentials less than 1 MW were segregated and summed to provide an estimate of total low head/low power potential in the area. Having hydropower potential estimates in such small increments allowed the low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies: conventional turbines, unconventional systems, and microhydro.

In order to calculate the hydropower potential of each stream segment, the hydrography in the region was derived using the U.S. Geological Survey's Elevation Derivatives for National Applications (EDNA) dataset. In addition to the hydrography, the dataset provided elevation data at the upstream and downstream ends of each stream segment, which were used to calculate hydraulic head. The dataset also allowed the calculation of the drainage area providing runoff to each stream segment. Overlaying the EDNA data with climatic data from the Parameter-elevation Regressions on Independent Slopes Model dataset provided the variables needed to calculate stream flow for each stream segment using regression equations developed specifically for each of the two hydrologic regions in the study area. Combining stream flow with hydraulic head provided the hydropower potential of the stream segment.

Because the hydrography used was "synthetic," stream segments were compared to streams in the U.S. Geological Survey's National Hydrography Dataset. Unconfirmed stream segments were eliminated from the datasets that were used to estimate total hydropower potentials. A GIS layer containing streams and areas that are excluded from development by statutory regulations was used to segregate excluded and nonexcluded stream segments. The amount of developed hydropower in the area provided by the Federal Energy Regulatory Commission's Hydroelectric Power Resources (HPRA) database was subtracted

from total, nonexcluded, hydropower potentials to produce estimates of available hydropower potentials.

The assessment estimated that the total hydropower potential of the study area is 15,000 MW. Of this amount, 1,000 MW is excluded from development. With 4,000 MW of developed hydropower in the area, the total available hydropower potential is estimated to be about 10,000 MW. Low head/low power potential makes up 1,500 MW of the total available potential. Division of the available low head/low power potential among low head/low power technology classes showed that 37% fell within the operating envelope of conventional turbines, 14% fell within the operating envelope of unconventional systems, and 49% fell within the operating envelope of microhydro technologies. In addition to the low head/low power potential, it is estimated that there are 3,000 MW of high head (30 ft or greater)/low power potential in the region. A map of the locations of low head/low power sites by technology class and high head/low power sites shows that conventional turbine sites and unconventional system sites are numerous throughout the region with the exception of Long Island, southern New Jersey, and the Delmarva Peninsula. Microhydro sites are abundant and exist everywhere in the area. High head/low power sites are abundant in the area with the exception of southern New Jersey, the Delmarva Peninsula, and eastern Virginia and are of particularly high density in the Appalachian Mountains.

The study showed that there is significant, available low power hydropower potential in the study area most of which corresponds to the operating envelope of existing turbine technology. This significant source of distributed power could be realized without the need for water impoundments.

For further information or comments, please contact:

Douglas G. Hall, Project Manager
Low Head/Low Power Hydropower Resource Assessment Project
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 3850
Idaho Falls, ID 83415-3850
Phone: (208) 526-9525
E-mail: *dgh@inel.gov*

Garold L. Sommers, Program Manager
Hydropower Program
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 3830
Idaho Falls, ID 83415-3830
Phone: (208) 526-1965
E-mail: *sommergl@inel.gov*

ACKNOWLEDGMENTS

The authors acknowledge and express their appreciation of the contributions to this study made by the U.S. Geological Survey (USGS): the Earth Resources Observation Systems (EROS) Data Center for producing the Elevation Derivatives for National Applications dataset for the North Atlantic and Middle Atlantic Hydrologic Regions, overlaying this dataset with climatic data, data processing programming, and producing the basic hydropower potential dataset used in the study; and Mr. K. G. Ries for his support as the USGS liaison to the Idaho National Engineering and Environmental Laboratory (INEEL) for the project. The authors acknowledge and express their appreciation of the technical guidance provided by Mr. R. T. Hunt (INEEL) and the review of this report by Mr. J. Flynn of the U.S. Department of Energy (DOE). The authors acknowledge and express their appreciation of the contribution of Mr. K. S. Reeves for the evaluation of developed power in the study area. Particular acknowledgment and appreciation is expressed for the foresight and guidance of Ms. P. A. Brookshier of the DOE Idaho Operations Office for requesting the assessment reported herein and guiding its development.

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FIGURES

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ACRONYMS

DOE — U.S. Department of Energy

EDNA — Elevation Derivatives for National Applications

An analytically derived, three-dimensional dataset in which hydrologic features have been determined based on elevation data from the NED resulting in three-dimensional representations of "synthetic streams" (stream path coordinates plus corresponding elevations) and an associated catchment boundary for each synthetic reach (based on 1:24K-scale data for the conterminous U.S. and 1:63,360-scale data for Alaska) (*Note: EDNA synthetic stream reaches do not uniformly coincide with NHD reaches. Conflation of EDNA and NHD features to improve the quality of both datasets is a later phase EDNA development.) (http://mn.water.usgs.gov/uzig/eros.reed.doc)*

FERC — Federal Energy Regulatory Commission

GIS — Geographic Information System

A set of digital geographic information such as map layers and elevation data layers, that can be analyzed using both standardized data queries as well as spatial query techniques.

HUC — hydrologic unit code

INEEL — Idaho National Engineering and Environmental Laboratory

MA — Middle Atlantic

NED — National Elevation Data

A three-dimensional representation of topographic features composed of geographic coordinates on a 30-m grid with corresponding elevations that numerically represent the topography based on 1:24K-scale data for the conterminous U.S. and 1:63,360-scale data for Alaska (available for the entire U.S. from U.S. Geological Survey [USGS]). (http://gisdata.usgs.net/ned/)

NA — North Atlantic

NHD — National Hydrography Dataset

A comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. (http://nhd.usgs.gov)

PRISM — Parameter-elevation Regressions on Independent Slopes Model

An expert system that uses point data and a digital elevation model to generate gridded estimates of climate parameters. *(http://www.ocs.orst.edu/prism/overview.html)*

NOMENCLATURE

Catchment	That portion on a drainage basin supplying runoff to a particular stream reach.
Drainage Area	The total surface area of the topography of a drainage basin.
Drainage Basin	The geographic area supplying runoff to a particular point on a stream equal to the area of all the catchments associated with upstream stream reaches connected to the point.
EDNA Stream Node	Starting point of an EDNA synthetic stream, a confluence, or an intermediate point on an EDNA stream defined as a result of having 5,000 National Elevation Data tiles (30 × 30 m) supplying runoff to the portion of an EDNA synthetic stream between this point and the EDNA node immediately upstream (Note: Each node has an associated catchment and is a pour point.)
EDNA Stream Reach	That portion of a EDNA synthetic stream between two EDNA stream nodes.
Pour Point Flow	The estimated flow of a stream reach equal to the runoff from the corresponding drainage basin.

Low Head/Low Power Hydropower Resource Assessment of the North Atlantic and Middle Atlantic Hydrologic Regions

1. INTRODUCTION

In June 1989, the U.S. Department of Energy (DOE) initiated the development of a National Energy Strategy to identify the energy resources available to support the expanding demand for the energy in the United States. Past efforts to identify and measure the undeveloped hydropower capacity in the U.S. have resulted in estimates ranging from about 70,000 MW to almost 600,000 MW. The Federal Energy Regulatory Commission's (FERC's) estimate was about 70,000 MW, and the U.S. Army Corps of Engineers' theoretical estimate was 580,000 MW. Public hearings conducted as part of the strategy development process indicated that the undeveloped hydropower resources were not well defined. One of the reasons was that no agency had previously estimated the undeveloped hydropower capacity based on site characteristics, stream flow data, and available hydraulic heads.

As a result, DOE established an interagency Hydropower Resources Assessment Team to ascertain the country's undeveloped hydropower potential. The team consisted of representatives from each power marketing administration (Alaska Power Administration, Bonneville Power Administration, Western Area Power Administration, Southwestern Power Administration, and Southeastern Power Administration), the Bureau of Reclamation, the Army Corps of Engineers, the FERC, the Idaho National Engineering and Environmental Laboratory (INEEL), and the Oak Ridge National Laboratory. The interagency team drafted a preliminary assessment of potential hydropower resources in February 1990. This assessment estimated that 52,900 MW of undeveloped hydropower energy existed in the United States.

Partial analysis of the hydropower resource database by groups in the hydropower industry indicated that the hydropower data included redundancies and errors that reduced confidence in the published estimates of developable hydropower capacity. DOE has continued assessing hydropower resources to correct these deficiencies, improve estimates of developable hydropower, and determine future policy. Modeling of the undeveloped hydropower resources in the United States identified 5,677 sites that have a total undeveloped capacity of about 70,000 MW (Connor et al. 1998). Consideration of environmental, legal, and institutional constraints resulted in an estimate of about 30,000 MW of viable, undeveloped U.S. hydropower resources.

The previous resource assessments have focused on potential projects that have a capacity of 1 MW or more. DOE identified a need to assess the U.S. hydropower resources for projects of less than 1 MW. In FY 2000, DOE initiated planning for an assessment of hydropower potential for low head (less than 30 feet) and low power (less than 1 MW) resources. The INEEL in conjunction with the U.S. Geological Survey recently completed the pilot low head/low power hydropower resource assessment (Hall et al. 2002). The principal objective of this pilot study was to develop and demonstrate a method of estimating the hydropower potential of a large geographic area. The method that was developed uses state-of-the-art digital elevation models and geographic information system tools. Using this method, the hydropower potential of every stream segment within a chosen study area is assessed. Summing the estimated hydropower potential of all the stream segments in the area provides an estimate of the total hydropower potential of the area.

The area of interest for the study described in this report was the combined area of the North Atlantic and Middle Atlantic Hydrologic Regions. This area encompasses the states of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New Jersey, and Delaware, most of

Maryland, and parts of the states of Vermont, New York, Pennsylvania, Virginia, and West Virginia. Having hydropower potential estimates in stream segment increments allowed the total hydropower potential in the study area to be divided into sub-categories: high power potential (1 MW or greater), high head/low power potential (less than 1 MW with 30 ft of hydraulic head or greater), and low head/low power (less than 1 MW with generally less than 30 ft of hydraulic head). It also allowed the low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies: conventional turbines, unconventional systems, and microhydro.

This report is organized by presenting a description of the study area, details of the technical method that was employed to perform the resource assessment, and the results of the assessment. It ends with conclusions based on the results and recommendations for further research and refinement of the technical method. Summaries of the hydropower potential results for each of the two hydrologic regions in the study area are presented in Appendix A.

2. STUDY AREA—NORTH ATLANTIC AND MIDDLE ATLANTIC HYROLOGIC REGIONS

The North Atlantic Hydrologic Region and Middle Atlantic Hydrologic Region are two of 21 hydrologic regions in the United States. The conterminous United States is divided into 18 hydrologic regions as shown in Figure 1, with the remaining three regions being Alaska, Hawaii, and Puerto Rico. The hydrologic regions have been numbered using a hydrologic unit code (HUC) of 1 through 21. The North Atlantic Hydrologic Region has been assigned a hydrologic unit code of 1 and is sometimes referred to as "HUC 1." The terms "HUC 1" and "North Atlantic Hydrologic Region" are used interchangeably. Similarly, the Middle Atlantic Hydrologic Region has been assigned a hydrologic unit code of 2, and is thus often referred to as "HUC 2." Figure 2 shows a map of these two hydrologic regions.

1.1 North Atlantic Region (HUC 1)

The North Atlantic Region covers most or all of the following New England states: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut. The New England Upland, a northern extension of the Appalachian Mountains, occupies the inland portion of the North Atlantic Region. The New England Upland consists of wooded mountains, many of which reach several thousand feet in elevation. The remainder of the region, the Seaboard Lowland, is a series of coastal plains and rolling low hills between the mountains and the sea. In Maine, rolling hills directly border the Atlantic Ocean, forming a rugged, irregular shoreline of alternating bays, peninsulas, and islands.

Although the North Atlantic Region lacks extensive navigable rivers, the abundant rainfall and rugged topography of the region has enabled its inhabitants to extract hydropower from numerous streams of all sizes. The use of hydropower in this region extends back to local cottage industries established during the colonial era. By the early 19th century, New England milltowns were exploiting local hydropower sources to power the nation's first factories. In this manner, the Industrial Revolution gained its first foothold on the North American continent.

1.2 Middle Atlantic Region (HUC 2)

The Middle Atlantic Region covers approximately half of the states of Vermont, New York, and Pennsylvania, the entirety of the states of New Jersey and Delaware, most of the state of Maryland, and parts of the states of Virginia and West Virginia. The principal geographic features of this region (from east to west) are the Atlantic Coastal Plain, the Piedmont, and the Appalachian Mountains. Inland from the Atlantic Coastal Plain lies the Piedmont, a relatively low, rolling plateau that extends the entire length of the Middle Atlantic Region. The Piedmont is a fertile agricultural region crossed by many rivers originating in the Appalachian Mountains. The Piedmont rises to meet the Appalachians, a major mountain chain that runs from Maine to Alabama. The principal feature of the Appalachian Mountains is the ridge and valley sequence, a northeast-trending series of alternating ridges and valleys formed by the folding and erosion of parallel rock layers.

Several major rivers originate in the Appalachians, flowing across the Piedmont to bays and inlets connecting to the Atlantic Ocean. These include (from north to south) the Hudson River, the Delaware River, the Susquehanna River, and the Potomac River. Many of these rivers are navigable and provided some of the earliest transportation corridors from the eastern U.S. to the interior of North America.

The climate of the region is temperate with abundant rainfall throughout the year. Temperatures are moderate near the southern coastal areas of the region, becoming cooler as one travels northward toward New York or inland from the coast.

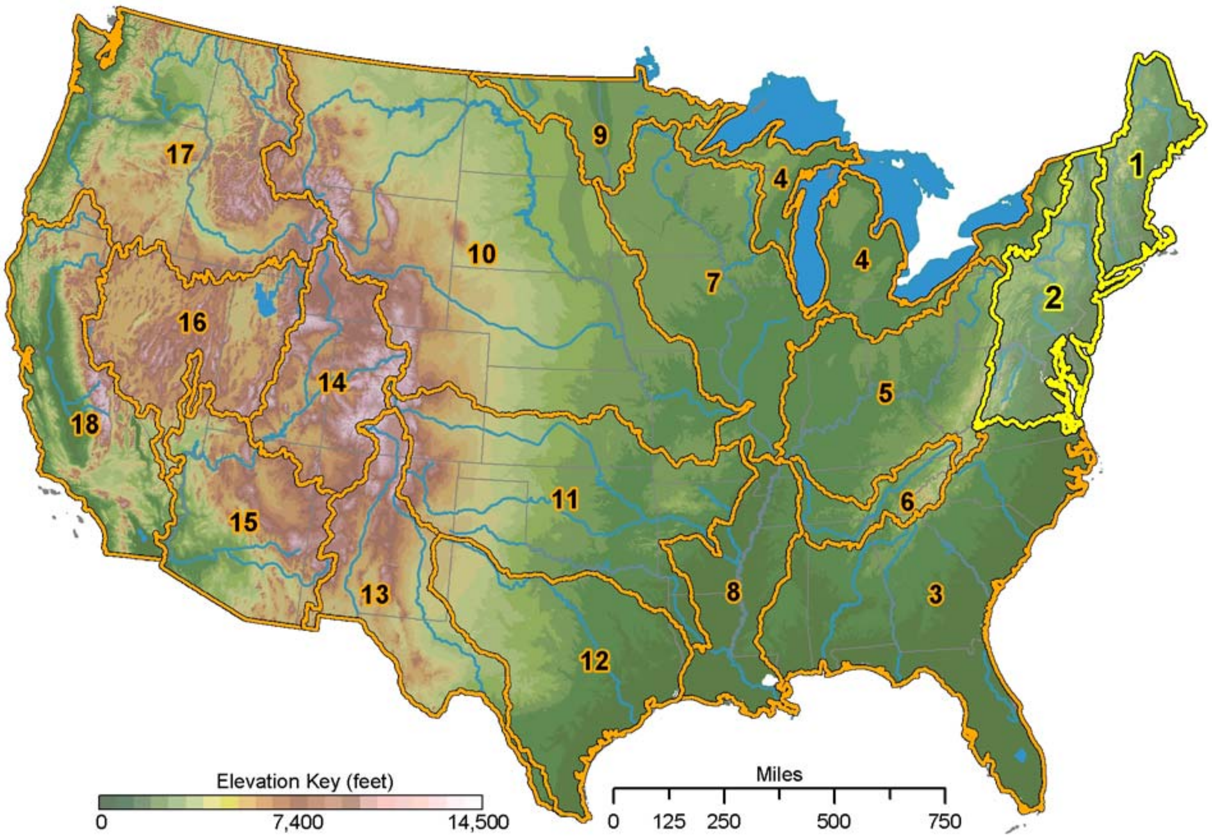

Figure 1. The 18 hydrologic units of the conterminous United States.

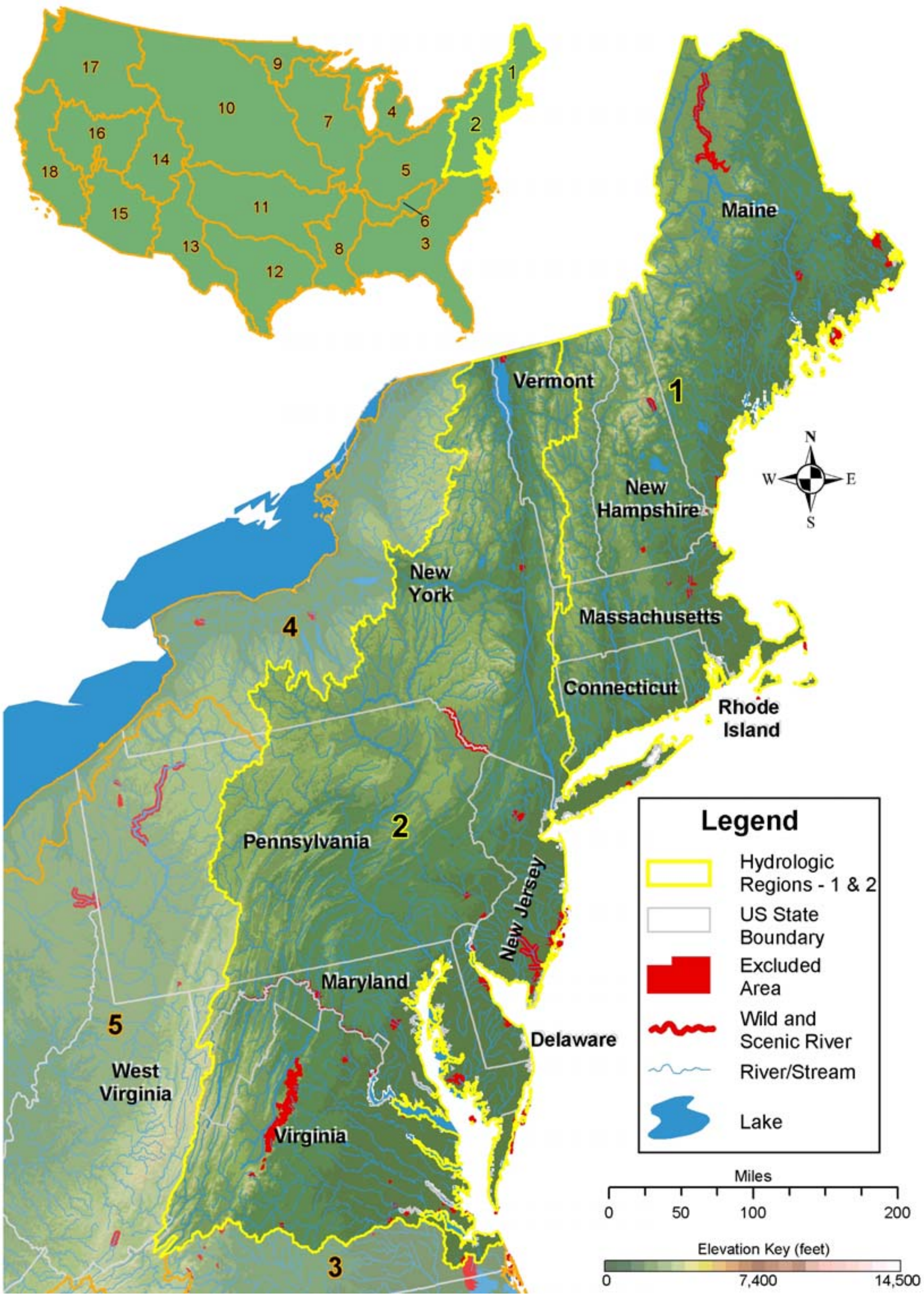

Figure 2. North Atlantic and Middle Atlantic Hydrologic Regions.

3. TECHNICAL APPROACH

The fundamental approach of this study was to calculate the hydropower potential of every stream reach within the study area. A stream reach was generally the stream segment between two confluences and had an average length of 2 miles. After producing a master set of reach power potentials, this set was filtered to account for waterways excluded from development and to produce subsets based on the operating envelopes of three classes of low head/low power hydropower technologies. Summing the resulting subsets of reach power potentials produced total power potentials of interest. Developed hydropower in the region was deducted to determine "available" power potentials. (Note: The term "available power potential" in this study simply equates to total, nonexcluded power potential minus developed power potential. No economic or development feasibility assessment was performed.)

The calculation of reach hydropower potential requires two values: the reach flow and the hydraulic head corresponding to the elevation difference between the upstream and downstream ends of the reach. The reach flow was the average of the calculated flows at the inlet and outlet of the reach. The flows were calculated using a regression equation in which drainage area, mean annual temperature, and mean annual precipitation were the independent variables. The reach hydraulic head was derived from the hydrography as defined by a digital elevation model.

The subsections that follow describe the details of the various aspects of the technical approach:

- Calculation of reach hydropower potential
- Filtering processes to validate streams, account for excluded waterways, and parse potentials between technology class operating envelopes
- Determination of available power potential based on developed hydropower.

3.1 Calculation of Stream Flow, Hydraulic Head, and Hydropower Potential

The calculation of the stream flow, hydraulic head, and subsequently, hydropower potential requires a three-dimensional representation of the hydrography and related drainage basin information. The three-dimensional hydrography provides the extent of stream networks and the elevation differences required to calculate hydraulic heads. Related drainage basin information provides essential data for the calculation of stream flows. While the National Hydrography Dataset (NHD) provides the best two-dimensional depiction of the U.S. hydrography, it does not provide the required elevation information or related drainage basin information. In order to obtain the required hydrography parameters, the Elevation Derivatives for National Applications (EDNA) dataset was used. This dataset provided the needed three-dimensional hydrography in the form of analytically derived stream networks and drainage areas associated with each stream reach that could be summed to produce the drainage basin supplying runoff to points of interest along a stream.

A graphical illustration of the hydrography related information provided by the EDNA dataset is shown in Figure 3. This figure shows synthetic stream reaches each with an associated, local runoff area or catchment shown as a colored area encompassing the reach. Flow rates were calculated at the downstream end of each reach, which has been termed the catchment "pour point." The drainage area supplying runoff at a pour point is equal to the sum of the areas of all the upstream catchments.

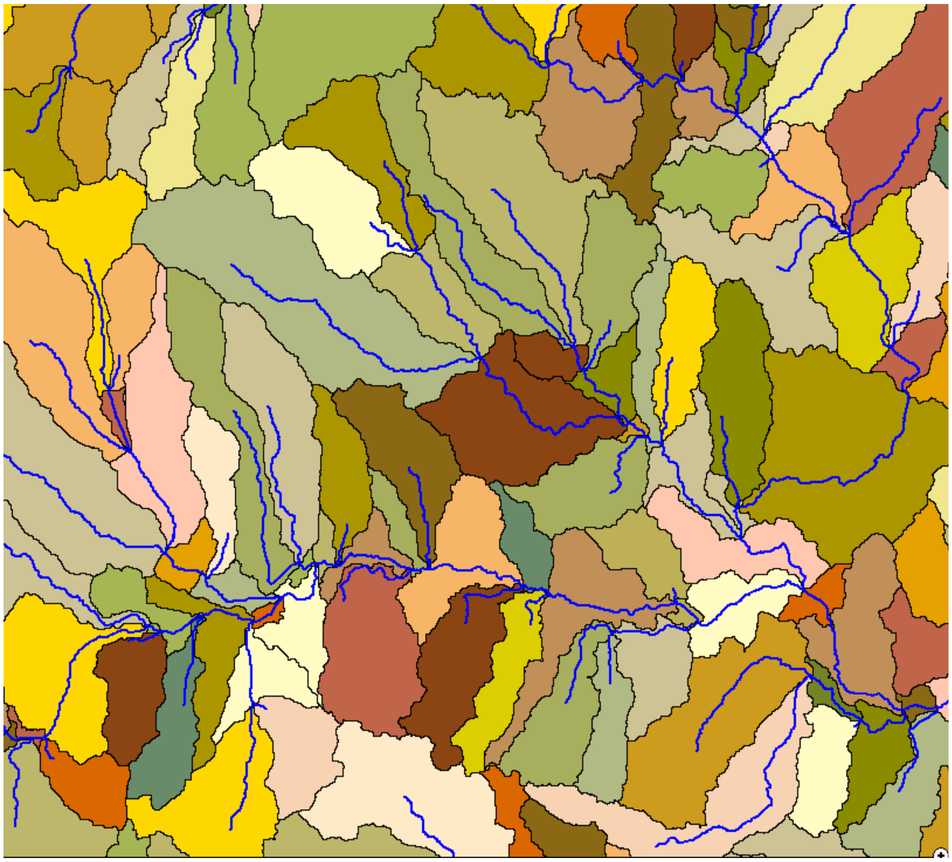

Figure 3. EDNA-derived catchments and synthetic streams.

Mean annual flow rates were calculated using regression equations developed specifically for the North Atlantic (NA) and Middle Atlantic (MA) Regions (Vogel et al. 1999).

$$Q_1 = e^{-9.4301} * A^{1.01238} * P^{1.21308} * T^{-0.5118}$$

$$Q_2 = e^{-2.7070} * A^{0.97938} * P^{1.6251} * T^{-2.0510}$$

where

Q_1 = mean flow for a site in the NA Region in cubic meters/second

Q_2 = mean flow for a site in the MA Region in cubic meters/second

A = drainage area in square kilometers

P = mean annual precipitation in millimeters/year

T = mean annual temperature in degrees Fahrenheit times 10.

These equations are based on gaged stream flows within the regions. The drainage area used is the sum of the upstream catchment areas. The other two variables, precipitation and temperature, were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 1994). Both temperature and precipitation data contained in the PRISM dataset are in grid format. The cells of the grids are much larger than the cells found in the EDNA dataset; therefore, an averaging function was used to calculate the mean annual precipitation and temperature for each catchment in the EDNA data. The catchment temperature and precipitation values were used to produce an area-weighted value for each drainage area. These values along with the drainage area were used to calculate the flow at the pour point of each catchment.

The hydraulic head associated with each stream reach was obtained using the elevation data in the EDNA dataset. The dataset provided the elevation at the upstream and downstream ends of the reach. The difference of these two elevation values was the hydraulic head or potential energy for the flow in the reach. While this was the correct value for the flow that entered the reach at the upstream end and transited the reach converting potential to kinetic energy, it was not the correct value for the portion of the flow at the reach exit or downstream end that was contributed by runoff from the local catchment. This added flow had hydraulic heads varying from the total reach hydraulic head to zero depending on where the runoff entered the stream. To account for this the following equation was used to calculate the hydropower potential of the reach:

$$P = \kappa\ [Q_i * H + (Q_o\text{-}Q_i) * H/2];\ H = z_i\text{-}z_o$$

where

P	=	power in kilowatts
κ	=	equals (1/11.8)
Q_i	=	flow rate at the upstream end of the stream reach in cubic feet per second
Q_o	=	flow rate at the downstream end of the stream reach in cubic feet per second
H	=	hydraulic head in feet
z_i	=	elevation at the upstream end of the stream reach in feet
z_o	=	elevation at the downstream end of the stream reach in feet.

The first quantity in the square brackets, $Q_i * H$, is the hydropower potential of the flow at the inlet to the reach, which experiences the full hydraulic head of the reach, H (difference between elevations at upstream and downstream ends of the reach). The quantity (Q_o-Q_i) is the part of the reach flow added by runoff from the associated catchment. For this flow, the hydraulic head varies from H to 0 depending on where runoff entered the reach. Therefore, an average value of H/2 was used for the local catchment runoff flow.

Algebraic manipulation shows that this equation reduces to:

$$P = \kappa H(Q_i+Q_o)/2$$

Thus, the reach hydropower potential is equal to a constant times the total reach hydraulic head times the average of the flow rates at the inlet (upstream end) and the outlet (downstream end) of the reach. It is also useful to note that Q_o is the pour point flow for the catchment associated with the reach, and Q_i is equal to the sum of the pour point flows of the catchments immediately upstream of the reach (catchment) of interest.

The calculations described above produced a master dataset that contained the following parameters for each stream reach:

- Reach characteristics
- Related catchment characteristics
- Reach outlet flow (catchment pour point flow)
- Reach hydraulic head
- Reach hydropower potential.

This master dataset was subsequently filtered to:

- Remove stream reaches that were not validated using the NHD
- Identify reaches that were excluded from development because of statutory protections
- Identify reaches having hydropower potentials within the low head/low power regime
- Divide low head/low power reaches into three subsets corresponding to the operating envelopes of three classes of low head/low power hydropower technologies.

These filtering operations are described in detail in the subsections that follow.

3.2 Validation of Synthetic Streams

The U.S. Geological Survey performed the processing that produced the Stage 1B version of the EDNA dataset in a consistent manner nationwide. It generally works well for areas having moderate to high relief and well-developed drainage. In certain types of terrain, however, the EDNA Stage 1B processing can create synthetic hydrography that deviates substantially from the actual hydrography

Figure 4 shows an overlay of EDNA synthetic streams and hydrography taken from the NHD for the study area. It is clear from this comparison that some of the synthetic stream reaches are not validated by the NHD and must be removed so as not to inflate the total hydropower potential estimate. To identify these "false" synthetic stream reaches and determine their effect on the regional, total hydropower potential, known stream locations found in the NHD were intersected with the catchments associated with EDNA synthetic streams. This allowed the master dataset to be divided into two subsets: one containing all the reaches whose catchment contained an NHD stream segment and one containing all the reaches whose catchment did not contain an NHD stream segment. The former was considered to be a validated master dataset, while the latter was a dataset containing all the "false" stream reaches showing through in red as illustrated in Figure 4. While this approach did not guarantee exact conflation of the EDNA synthetic streams with the NHD hydrography, it did ensure that an NHD stream segment existed within the catchment area, averaging 3 square miles that encompassed the synthetic reach.

In order to evaluate the effect of the "false" stream reaches on total hydropower potential, the hydropower potentials of the reaches in the false reach dataset were summed and compared to the sum of the hydropower potentials of all the stream reaches in the master dataset. It was found that 0.8% of the total potential power calculated for the study area using the master dataset is due to false stream segments.

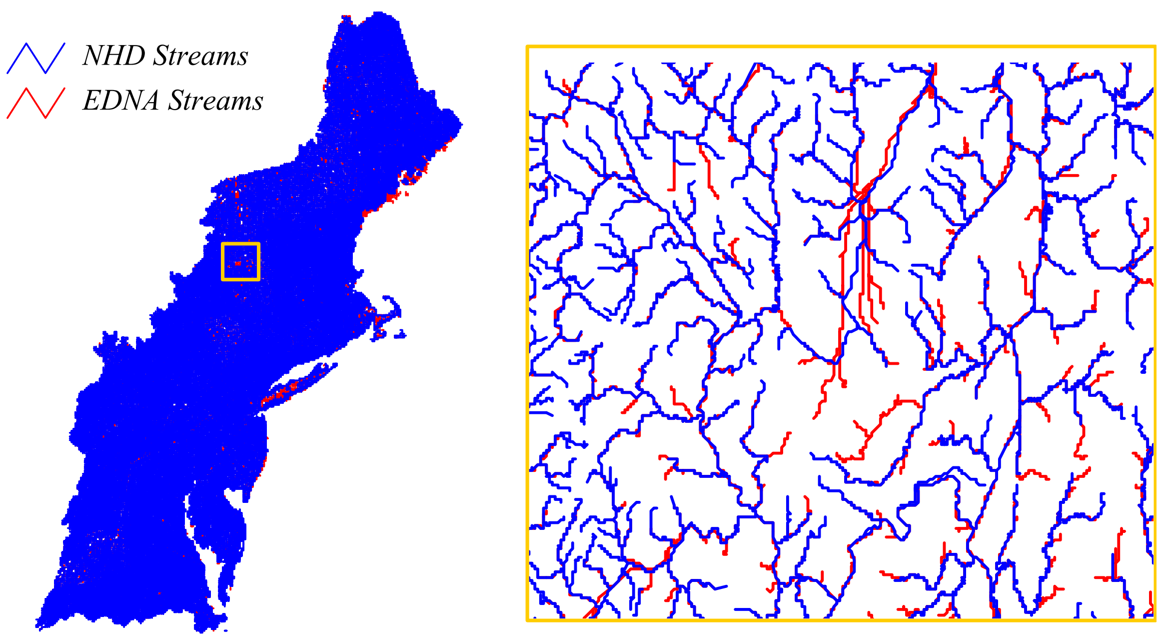

Figure 4. NHD streams overlaying EDNA synthetic streams in the study area.

3.3 Identification of Excluded Waterways and Hydropower Potential

As a general rule, hydropower development is prohibited in certain protected areas, such as national parks, national monuments, or along federally designated wild and scenic rivers. Protected areas such as these were designated as "excluded areas." Catchments that overlap any portion of these "excluded areas" were designated as "excluded catchments." The hydropower potential associated with the stream reaches in these excluded catchments was calculated and was subsequently subtracted from the hydropower potentials of interest for the study area, so that it would not contribute to available hydropower potential.

3.3.1 Classes of Excluded Waterways

Two geographic information system (GIS) data layers from the National Atlas of the United States were used to locate excluded areas. The first layer, "Federal and Indian Lands," contains the boundaries of all federal lands in the United States, subdivided into categories such as national parks, national monuments, Indian reservations, military bases, and DOE sites. The second layer, "Parkways and Scenic Rivers," contains federally protected linear features such as National Wild and Scenic Rivers and National Parkways. Both GIS data layers are available online from the National Atlas of the United States website at *http://www.nationalatlas.gov/atlasftp.html*.

The two above-mentioned GIS data layers provide comprehensive nationwide information regarding federally protected lands. States, regional jurisdictions, and local jurisdictions have also designated protected areas that are most likely excluded from hydropower development. However, information regarding these protected areas is scattered among numerous state, regional, and local government agencies. Much of this information is not yet in digital format, and much of the digital data is not available online. Determining the boundaries of lands protected by nonfederal agencies would have entailed contacting a large number of agencies within the eight states in the study area and collecting and digitizing multiple paper datasets in a variety of formats. Such an effort was beyond the scope of the project. Therefore, only nationwide datasets of federal lands were used to determine the extent of excluded areas.

The categories of federal lands listed in the GIS dataset "Federal and Indian Lands" were reviewed to determine categories that defined excluded areas. Based on this review, the following categories of federal lands were selected as excluded areas:

- National battlefields
- National historic parks
- National parks
- National parkways
- National monuments
- National preserves
- National wildlife refuges
- Wildlife management areas
- National wilderness areas.

All the federal lands in these categories were used to create an "excluded federal lands" GIS data layer. Similarly, all national wild and scenic rivers were extracted from the National Wild and Scenic Rivers and National Parkways data layer to create a GIS data layer composed exclusively of Wild and Scenic Rivers. Because the "wild and scenic rivers data layer" contained only the rivers themselves, but no adjoining land, all land within one kilometer of a wild and scenic river reach was designated as an excluded area. These areas were combined with excluded federal lands to create a final "excluded area" GIS data layer that contains the boundaries of all lands to be excluded from hydropower development.

3.3.2 Methodology for Identifying Excluded Stream Reaches

The final excluded area data layer was intersected with the EDNA catchment data layer to identify catchments containing stream reaches that should be excluded from consideration as sources of potential hydropower. Two data subsets resulted: one containing data for reaches that were excluded from hydropower development and one containing data for reaches that were not excluded.

3.4 Determining Developed Hydropower Capacity in the Study Area

The developed hydropower capacity within the study area was taken from Federal Energy Regulatory Commission's *Hydroelectric Power Resources Assessment (HPRA) Database* (FERC 1998). The developed capacities of plants in the study area were summed to determine the total developed hydroelectric capacity in the region.

3.5 Identification of Low Head/Lower Power Stream Reaches

The low head/low power regime is defined by the following two criteria:

- All hydropower potential less than 100 kW (microhydro)
- Hydropower potential greater than or equal to 100 kW but less than 1 MW with hydraulic head less than 30 ft.

The low head/low power regime is shown graphically in Figure 5.

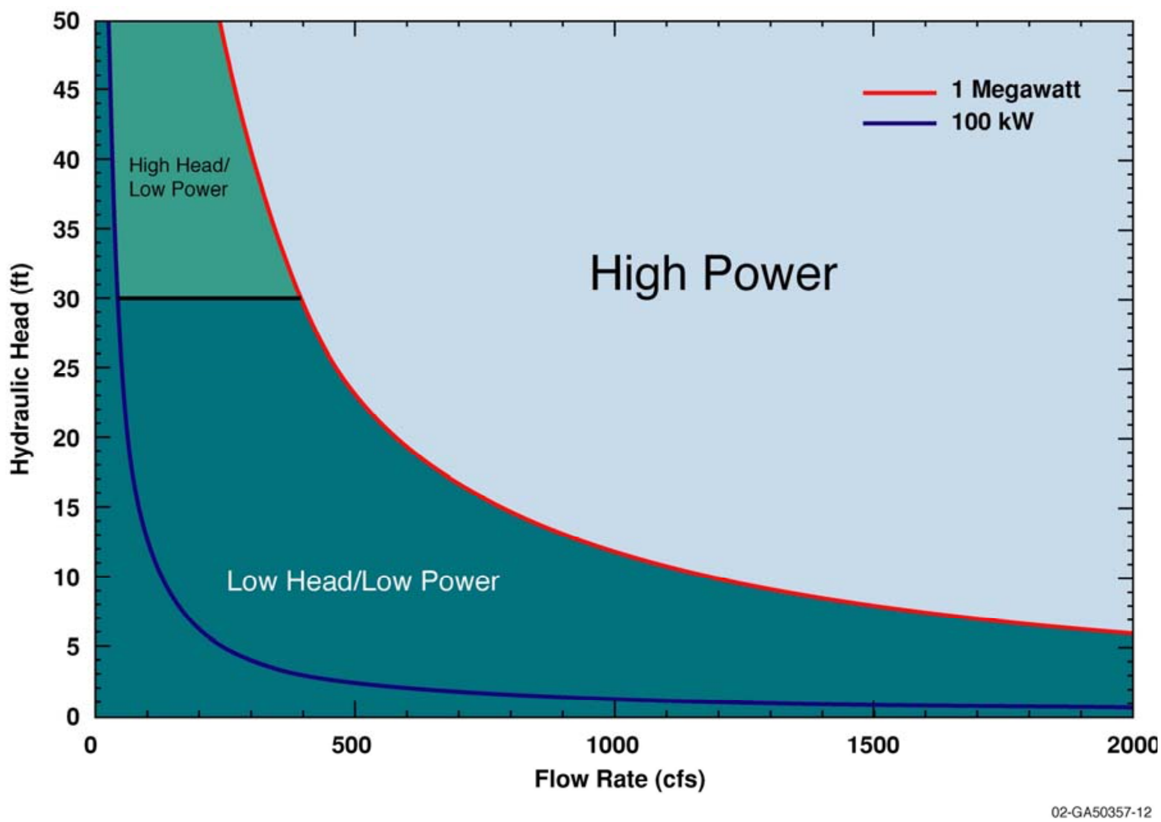

Figure 5. The low head/low power regime.

Standard database query techniques were applied to the validated master dataset described in Subsection 3.2 using the criteria for low head/low power as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the low head/low power region. These reaches were also filtered as described in Subsection 3.3 to identify the low head/low power reaches that were excluded and not excluded from development.

3.6 Identification of Stream Reaches Corresponding to the Operating Envelopes of Three Classes of Low Head/Low Power Hydropower Technologies

The low head/low power regime shown in Figure 5 has been divided into the operating envelopes of three classes of low head/low power technologies:

- Microhydro technologies—Power less than to100 kW
- Conventional turbines—Power greater than or equal to 100 kW, but less than 1 MW AND hydraulic head greater than or equal to 8 ft, but less than 30 ft
- Unconventional systems—Power greater than or equal to100 kW, but less than 1 MW AND hydraulic head less than 8 ft.

These operating envelopes are shown graphically in Figure 6.

Standard database query techniques were applied to the dataset containing low head/low power reaches identified as described in Subsection 3.5. The criteria for defining each of the technology class operating envelopes were used as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the operating envelopes. These reach subsets were also filtered as described in Subsection 3.3 to identify the reaches that were excluded and not excluded from development.

3.7 Calculation of Total Hydropower Potentials of Interest

Total hydropower potentials of interest were calculated by summing the reach hydropower potentials within each of the datasets that were determined as described in the previous subsections. "Available" hydropower potential was determined by accounting for the corresponding amount of developed hydroelectric capacity. No feasibility analysis was performed to further refine the estimates of available hydropower potential.

3.7.1 Total Hydropower Potential

Summing of the reach hydropower potentials in the validated master dataset described in Subsection 3.2 yielded the estimated total hydropower potential for the region.

3.7.2 Total Excluded and Nonexcluded Hydropower Potential

Summing of the reach hydropower potentials in the excluded and nonexcluded reach datasets described in Subsection 3.3 yielded the estimated total, excluded, and nonexcluded hydropower potentials for the region.

3.7.3 Total Available Hydropower Potential

The total available hydropower potential was determined by subtracting the total developed hydroelectric capacity in the region from the total nonexcluded hydropower potential.

3.7.4 Low Head/Low Power Hydropower Potentials

The total, excluded, nonexcluded, and available hydropower potentials for the low head/low power regime were calculated using the same processing as described above to obtain the total values. However, in this case the dataset containing all low head/low power reaches and the excluded and nonexcluded subsets of this dataset were used. The available potential was equal to the

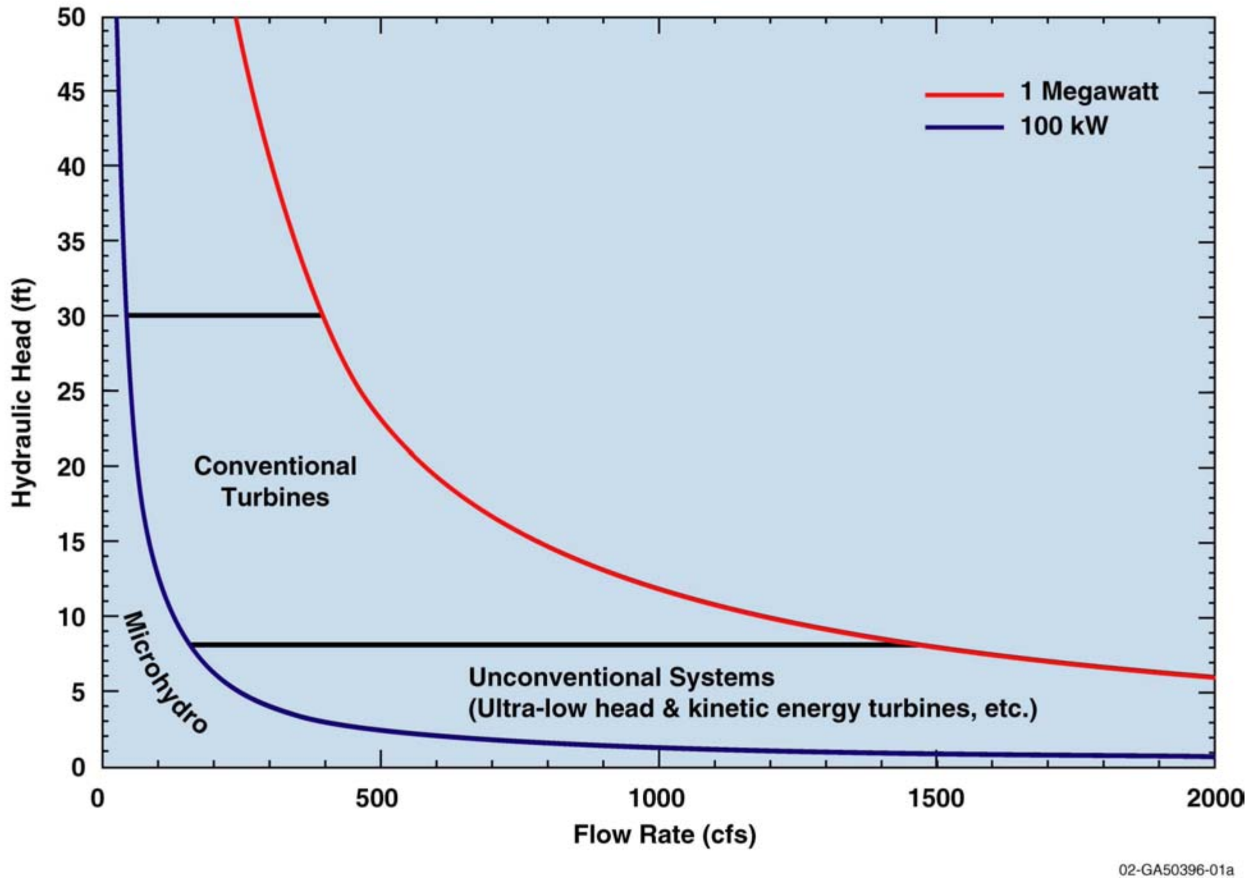

Figure 6. Operating envelopes of three classes of low head/low power hydropower technologies.

nonexcluded potential, because no developed hydroelectric capacity in the low head/low power regime was listed in the FERC reference.

3.7.5 Hydropower Potentials By Hydropower Technology Class

The total, excluded, nonexcluded, and available hydropower potentials for each hydropower technology class were also calculated using the same processing as described above to obtain the low head/low power values. Each set of hydropower potentials for the three classes was calculated using a set of reach hydropower potentials corresponding to the technology class operating envelope and the excluded and nonexcluded subsets. Available hydropower potential for each technology class was equal to the nonexcluded value because of the absence of developed hydroelectric capacity in the low head/low power regime.

4. RESULTS

The results of the calculations described in Subsection 3.7 are presented in this section. The results are presented in four sets of total hydropower potentials of interest for the study area:

- Total power
- High head/low power
- Low head/low power
- Low head/low power by technology class.

The accuracy of the hydropower potential estimates is dependent on the accuracy of the individual stream reach hydropower potentials that were summed to produce total values of interest. The calculated reach flow rates had a standard error of ±9% and ±12% in the NA Region and MA Region, respectively. Because of the direct relationship of hydropower potential and flow rate (see Subsection 3.1), the standard error of the reach hydropower potential values was also at least ±9% or ±12%, respectively. If the errors are uniformly distributed, the accuracy of a total value produced by summing a large number of reach hydropower potentials may be better than the accuracy associated with the values that were summed.

Table 1 presents a summary of the results. These results are discussed in the subsections that follow.

4.1 Total Hydropower Potential

The sum of all the validated reach hydropower potentials in the study area provided an estimate of 14,914 MW of hydropower potential in the area. FERC has cataloged 3,941 MW of developed hydroelectric capacity in the area. The total hydropower potential of stream reaches excluded from development was 1,022 MW. Subtracting the developed and excluded hydropower potentials from the total provides an estimate of 9,952 MW of hydropower in the area that has not been developed and is not excluded from development.

This available hydropower potential figure is an upper limit and provides an indicator of whether further investigation is warranted. Additional exclusions by state agencies that were beyond the scope of the project to research would most certainly reduce this number. The number would no doubt be further significantly reduced based on the engineering and economic feasibility of specific sites.

The distribution of total hydropower potential between developed, excluded, and available power is shown graphically in Figure 7. This figure shows that only 26% of the hydropower potential in the region has been developed. The hydropower potential excluded by federal statute is 7% of the total, regional hydropower potential. This leaves 67% or two-thirds of the potential in the area available for possible development.

4.2 Available Power Potential by Regime

The distribution of the total, available hydropower potential in the area (9,952 MW) between the high power (greater than or equal to 1 MW), high head/low power (power less than 1 MW and hydraulic head of 30 ft or more, excluding the microhydro operating envelope), and low head/low power is shown graphically in Figure 8. This figure shows that slightly more than 50% of the available hydropower potential is in the high power regime and slightly less than 50% is in the low power regime. Of the available hydropower potential in the low power regime, approximately two-thirds is high head (30 ft or greater) potential (31% of the available potential), and one-third is low head (less than 30 ft) potential (15% of the available potential).

Table 1. Summary of results of hydropower resource assessment of the combined North Atlantic and Middle Atlantic Hydrologic Regions.

Power in MW	Total	Developed	Excluded	Available
TOTAL POWER	**14,914**	**3,941**	**1,022**	**9,952**
TOTAL HIGH POWER	**10,023**	**3,836**	**811**	**5,376**
High Head/High Power	**6,595**	**3,417**	**424**	**2,754**
Low Head/High Power	**3,428**	**419**	**387**	**2,622**
TOTAL LOW POWER	**4,891**	**105**	**211**	**4,576**
High Head/Low Power	**3,265**	**38**	**163**	**3,065**
Low Head/Low Power	**1,626**	**67**	**48**	**1,511**
Conventional Turbine	649	65	16	568
Unconventional	222	0	11	210
Microhydro	756	3	20	733

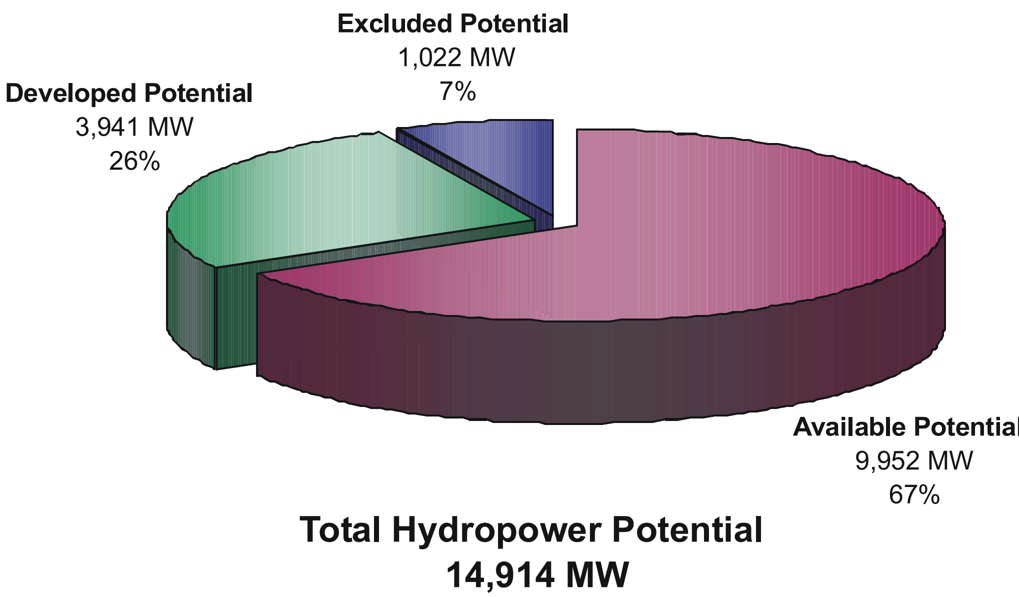

Figure 7. Distribution of total hydropower potential in the combined North Atlantic and Middle Atlantic Hydrologic Regions.

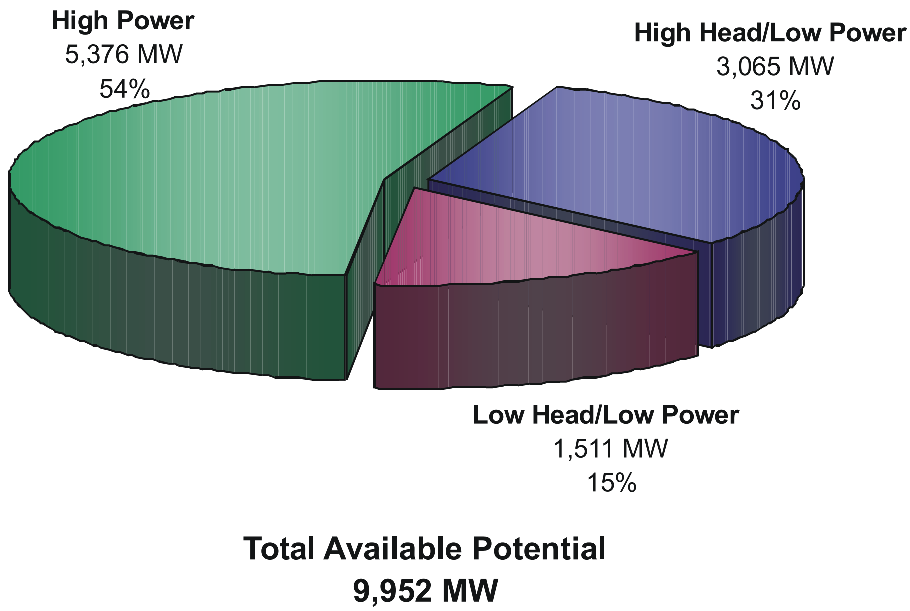

Figure 8. Distribution of available hydropower potential in the combined North Atlantic and Middle Atlantic Hydrologic Regions.

4.3 Low Head/Low Power Potential

The sum of all the validated reach hydropower potentials having values that fell within the low head/low power regime shown in Figure 5 provided an estimate of 1,626 MW of low head/low power hydropower potential in the study area. FERC listed 67 MW of developed hydropower capacity that fell within the low head/low power regime. The total hydropower potential of the reaches that were both low head/low power and were excluded from development was 48 MW. Subtracting the developed and excluded hydropower potentials from the total low head/low power potential provides an estimate of 1,511 MW of low head/low power hydropower in the area that has not been developed and is not excluded from development. As mentioned in the previous subsection, this figure is an upper limit and is subject to reductions due to exclusion by state agencies and feasibility assessments.

The validated reach hydropower potentials having values that fell within each of the operating envelopes of the three classes of low head/low power hydropower technologies shown in Figure 6 were summed to provide an estimate of the total hydropower potential associated with each technology class. This resulted in estimates of 649 MW, 222 MW, and 756 MW of hydropower potential for conventional turbines, unconventional systems, and microhydro technologies, respectively. The total hydropower potentials that were either developed or excluded from development and corresponded to each of the operating envelopes were 81 MW, 11 MW, and 23 MW, respectively. Subtracting the developed and excluded potentials from the total potential for each technology class resulted in estimates of available hydropower potential of 568 MW, 210 MW, and 733 MW, respectively. As stated in the previous two subsections, these availability estimates do not account for exclusions by state agencies or reductions resulting from feasibility assessments.

The distribution of low head/low power hydropower potential among the three classes of technologies is shown in Figure 9. This figure shows that 37% of the available low head/low power hydropower potential is captured by the operating envelope of conventional turbines, which would require relatively little development. Half (49%) is captured by the operating envelope of microhydro technologies. The remaining 14% corresponds to unconventional systems.

The geographic locations of existing hydroelectric plants, low head/low power potential sites by technology class, and high head/low power potential sites are shown in Figure 10. The first panel (a) of this figure illustrates the high density of hydroelectric plants in New England and the relatively few plants in the remainder of the study area. The second panel (b) showing low head/low power potential sites shows that microhydro potential exists through the area. Sites for conventional turbines and unconventional systems exist throughout the area with the exception of Long Island, southern New Jersey, and the Delmarva Peninsula, which includes the state of Delaware and the part of the state of Maryland west of the Chesapeake Bay. The third panel (c) shows a high density of high head/low power potential sites in the Appalachian Mountains, but also in the Piedmont Region in eastern Pennsylvania and southeast New York. High head/low power potential is even shown to be present in the Atlantic Coastal Plain area in Connecticut and Rhode Island, but is shown not to be present in the same parts of the area where low head/low power sites are absent and in eastern Virginia.

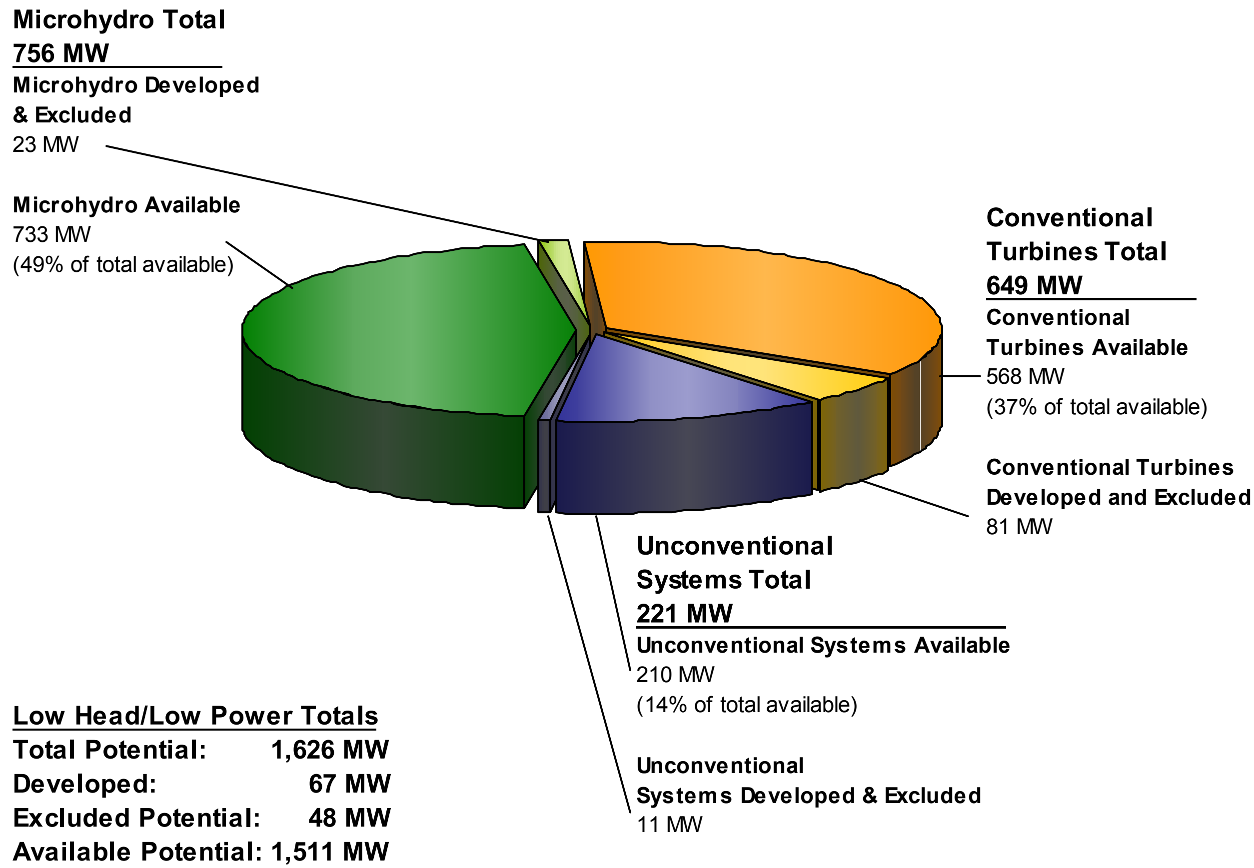

Figure 9. Distribution of low head/low power hydropower potential in the study area among three low head/low power hydropower technology classes.

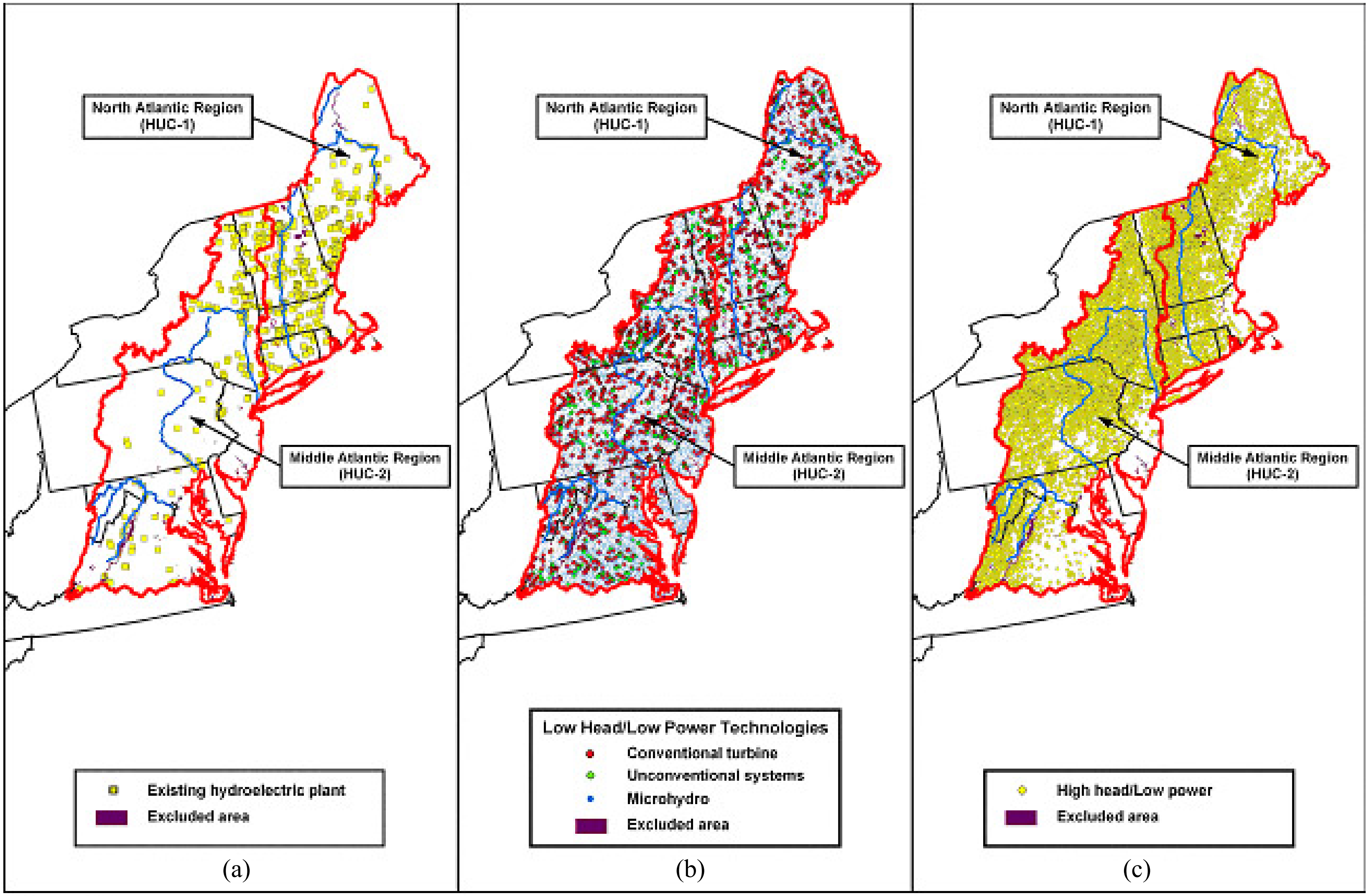

Figure 10. Existing hydroelectric plants (a), low head/ low power potential sites (b), high head/low power potential sites (c) in the North Atlantic and Middle Atlantic Hydrologic Regions.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in an estimate of approximately 10,000 MW of available hydropower potential in the combined area of the North Atlantic and Middle Atlantic Hydrologic Regions. Slightly less than half or 4,600 MW is low power hydropower potential of which approximately 1,500 MW is low head potential. These estimates are sufficiently large to warrant further research regarding possible siting of low power hydropower installations in the region. Low power sites are sufficiently numerous and uniformly distributed over the region to offer significant sources of distributed power without the need for reservoirs.

The study has shown that 3,065 MW of available high head/low power potential and an additional 568 MW or 37% of available low head/low power hydropower potential fall with the operating envelope of existing, conventional turbine technology. Thus this fraction of the available hydropower potential could be realized without investments in basic research. Sixty-three percent of the available low head/low power hydropower potential corresponds to technologies (microhydro and unconventional systems) that would require additional research and development; although, some units currently exist that could be put into service.

This study and the two prior studies of the Arkansas White Red Region (Hall et al. 2002) and Pacific Northwest Region (Hall et al. 2002) have shown that it is possible to obtain an estimate of the hydropower potential of the entire United States that is based on minutely detailed hydrography. Application of the technical approach used in these studies to each of the 18 hydrologic units in the conterminous U.S. and ultimately the State of Alaska will allow assessment of the available hydropower potential of each region and identification of the type of technology best suited to realize that potential. A composite of these regional results will provide a spatial distribution of available hydropower potential in the conterminous U.S. as well as an estimate of total available U.S. potential. Given the demonstrated possibility of obtaining this important, fundamental information, we recommend the hydropower potential of the 14 remaining hydrologic regions in the conterminous U.S. and the State of Alaska be assessed using the same technical approach.

Early in the expanded study, we recommend that results of stream reach flow rate and hydropower potential calculations be benchmarked against known, gauged flows and installed hydropower capacity. The study should be driven by the availability of EDNA synthetic hydrography that has been validated by the U.S. Geological Survey in its ongoing efforts to obtain correlation between EDNA hydrography and that provided by the more accurate NHD. If possible, equations that predict median rather than mean annual stream flow should be used to obtain better temporal estimates of hydropower potential.

6. REFERENCES

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Appendix A

Summary Results for the North Atlantic and Middle Atlantic Hydrologic Regions

Appendix A

Summary Results for the North Atlantic and Middle Atlantic Hydrologic Regions

This appendix contains summary results of the hydropower assessments of the of the North Atlantic (HUC 1) and Middle Atlantic (HUC 2) Hydrologic Regions. These regions collectively made up the study area and are considered in aggregate in the results that are presented in the body of the report.

A-1. North Atlantic Hydrologic Region

The topographic and hydrographic features of the North Atlantic Region are shown in Figure A-1. The results of the hydropower assessment of the region are presented in Table A-1. The distribution of total hydropower potential between developed, excluded, and available potential is shown in Figure A-2. Similar to the study area as a whole, approximately one-third of the regional potential has been developed or is excluded from development leaving almost two-thirds of the potential available for possible development.

The distribution of the 3,556 MW of available hydropower potential is shown in Figure A-3. The distribution is identical to that of the study area at large. Slightly more than half of the available potential, is high power (1 MW or greater) potential, and slightly less than half is low power (less than 1 MW) potential. Two-thirds of the low power potential is high head (30 ft or greater) potential, and one-third is low head (less than 30 ft) potential.

Table A-1. Summary of results of hydropower resource assessment of the North Atlantic Hydrologic Region.

Power in MW	Total	Developed	Excluded	Available
TOTAL POWER	**5,660**	**1,881**	**223**	**3,556**
TOTAL HIGH POWER	**3,876**	**1,807**	**137**	**1,932**
High Head/High Power	**2,768**	**1,541**	**112**	**1,116**
Low Head/High Power	**1,107**	**266**	**25**	**816**
TOTAL LOW POWER	**1,784**	**74**	**86**	**1,624**
High Head/Low Power	**1,192**	**23**	**69**	**1,101**
Low Head/Low Power	**592**	**51**	**18**	**523**
Conventional Turbine	234	50	7	178
Unconventional Systems	83	0	5	78
Microhydro	275	2	6	268

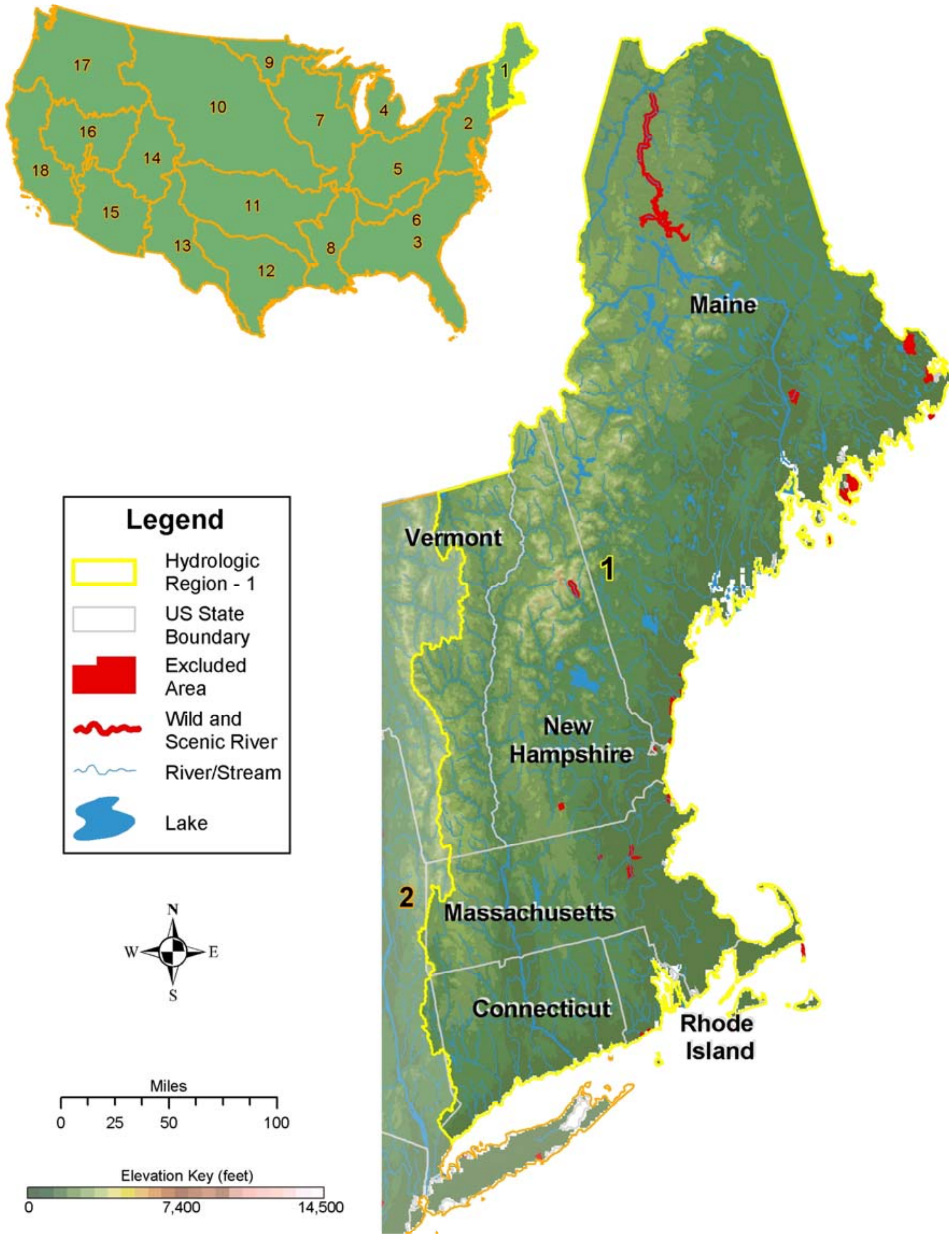
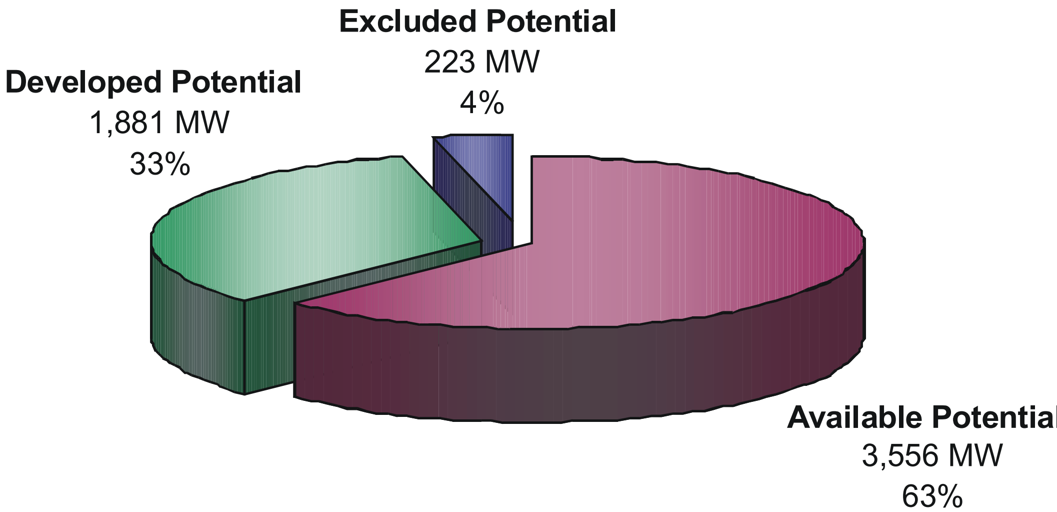
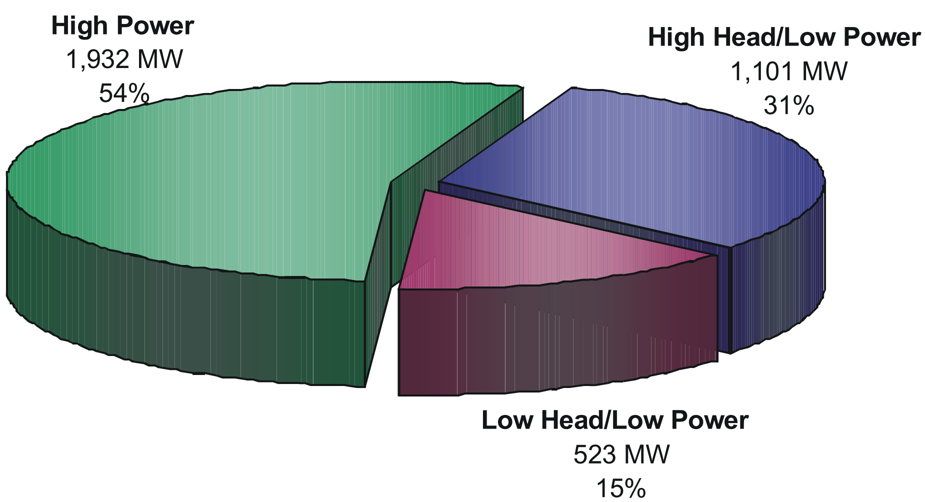


Figure A-1. North Atlantic Hydrologic Region (HUC 1).



Total Hydropower Potential
5,660 MW

Figure A-2. Distribution of total hydropower potential in the North Atlantic Hydrologic Region.



Total Available Potential
3,556 MW

Figure A-3. Distribution of available hydropower potential in the North Atlantic Hydrologic Region.

The distribution of the low head/low power potential between the operating envelopes of three low head/low power technology classes is shown in Figure A-4. Again, the distribution is nearly identical to the study area at large. Approximately half of the available low head/low power potential is in the microhydropower regime, approximately one-third is in the conventional turbine regime, and about 15% is in the unconventional systems regime.

A-2. Middle Atlantic Hydrologic Region

The topographic and hydrographic features of the Middle Atlantic Region are shown in Figure A-5. The results of the hydropower assessment of the Middle Atlantic Region are presented in Table A-2. The distribution of total hydropower potential between developed, excluded, and available potential is shown in Figure A-6. Similar to the study area as a whole, approximately one-third of the regional potential has been developed or is excluded from development leaving almost two-thirds of the potential available for possible development. The distribution of the 6,396 MW of available hydropower potential is shown in Figure A-7. The distribution is identical to that of the study area at large. Slightly more than half of the available potential is high power (1 MW or greater) potential, and slightly less than half is low power (less than 1 MW) potential. Two-thirds of the low power potential is high head (30 ft or greater) potential, and one-third is low head (less than 30 ft) potential.

The distribution of the low head/low power potential between the operating envelopes of three low head/low power technology classes is shown in Figure A-8. Again, the distribution is very similar to the study area at large. Approximately half of the available low head/low power potential is in the microhydropower regime, 40% is in the conventional turbine regime, and 13%, in the unconventional systems regime.

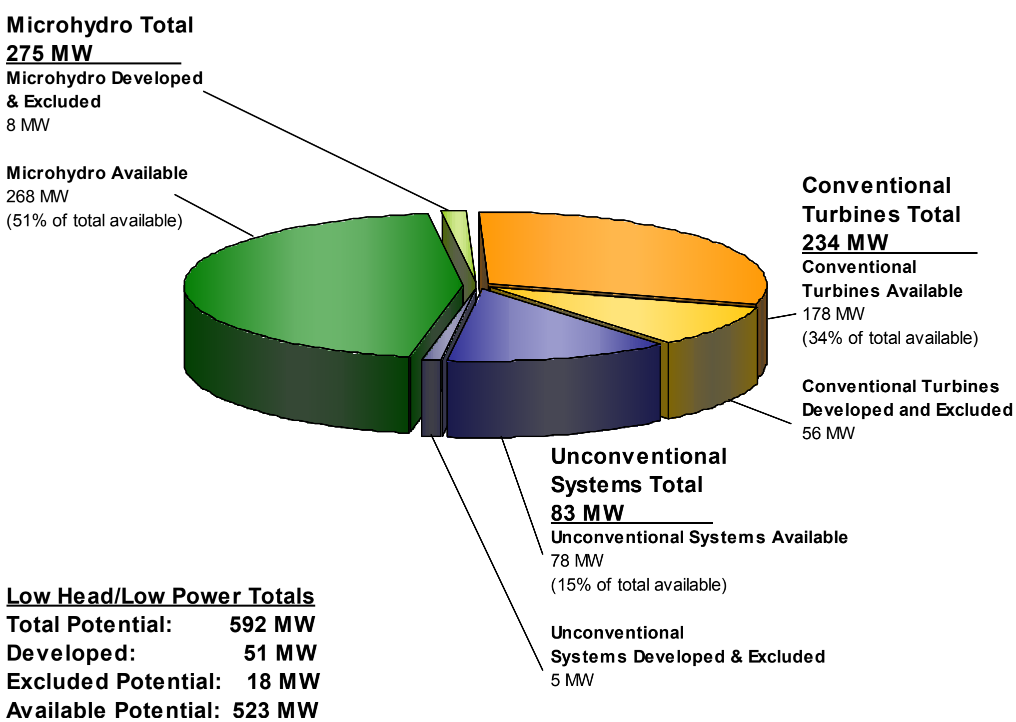


Figure A-4. Distribution of low head/low power hydropower potential in the North Atlantic Region among three low head/low power hydropower technology classes.

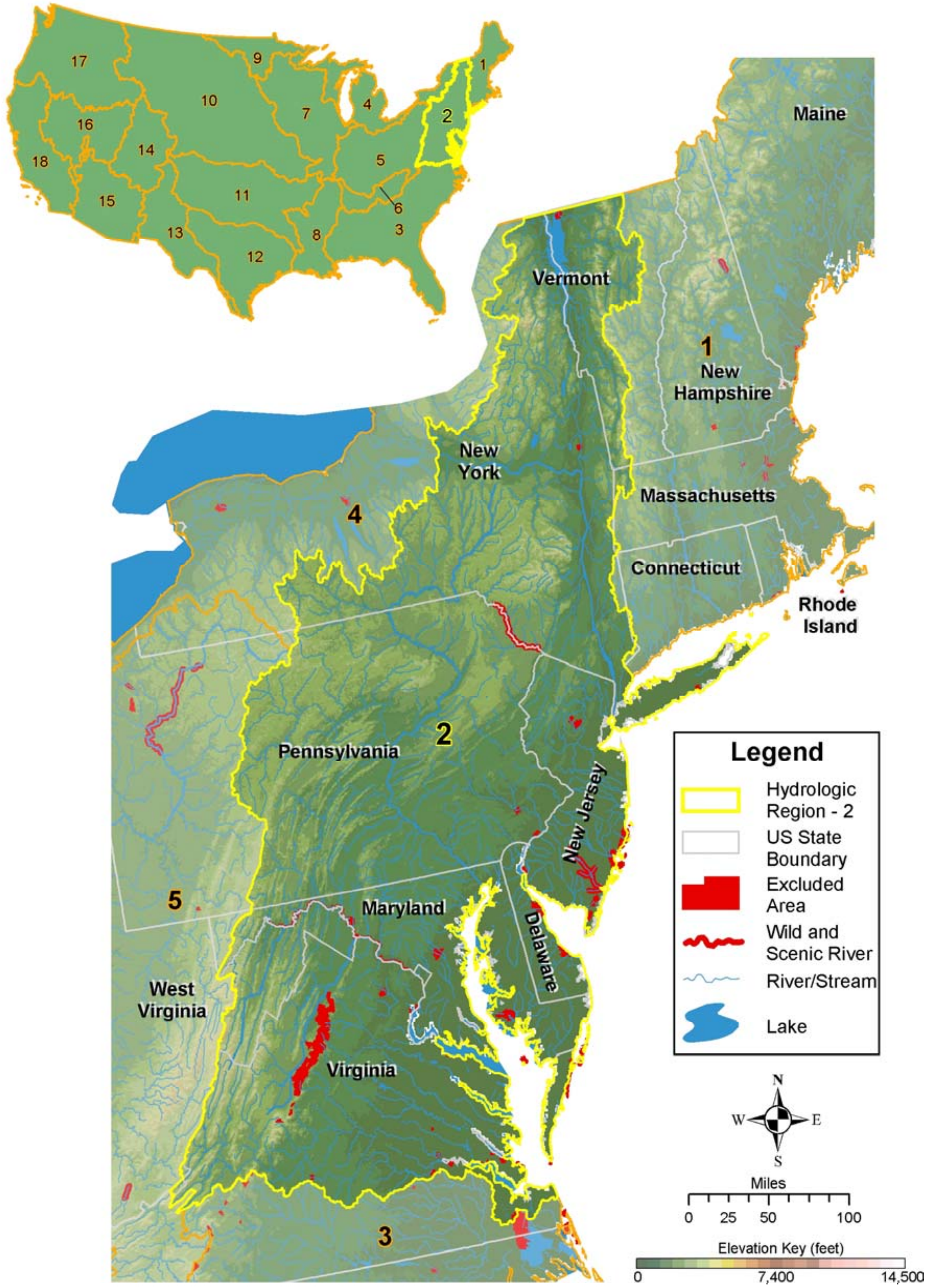


Figure A-5 Middle Atlantic Hydrologic Region (HUC 2).

Table A-2. Summary of results of hydropower resource assessment of the Middle Atlantic Hydrologic Region.

Power in MW	Total	Developed	Excluded	Available
TOTAL POWER	**9,254**	**2,060**	**798**	**6,396**
TOTAL HIGH POWER	**6,147**	**2,029**	**674**	**3,444**
High Head/High Power	**3,827**	**1,876**	**312**	**1,639**
Low Head/High Power	**2,320**	**153**	**362**	**1,805**
TOTAL LOW POWER	**3,107**	**30**	**124**	**2,952**
High Head/Low Power	**2,073**	**14**	**94**	**1,964**
Low Head/Low Power	**1,034**	**16**	**30**	**988**
Conventional Turbine	415	15	10	390
Unconventional	139	0	6	132
Microhydro	480	1	14	465

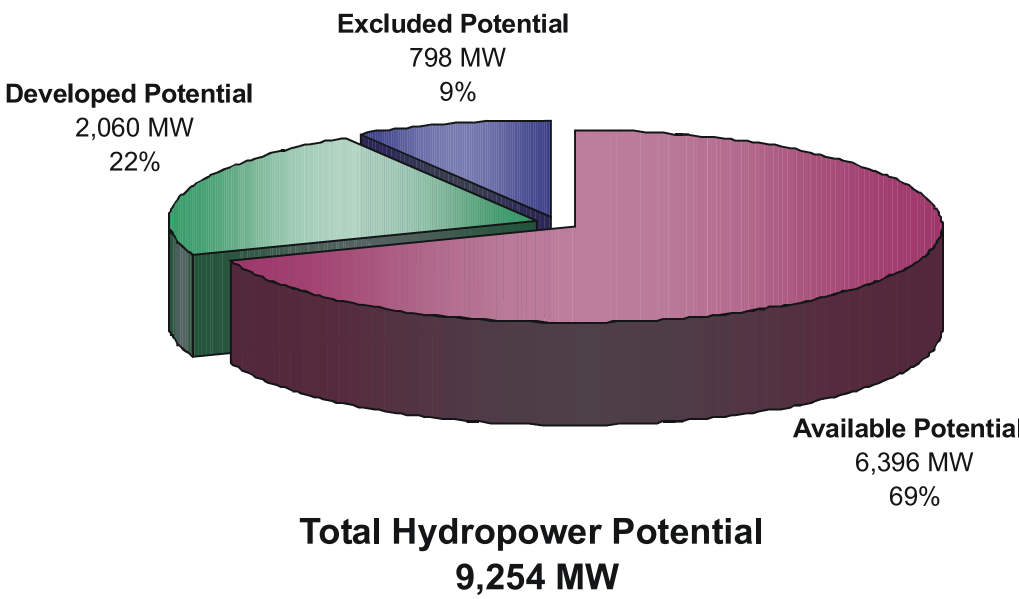


Figure A-6. Distribution of total hydropower potential in the Middle Atlantic Hydrologic Region.

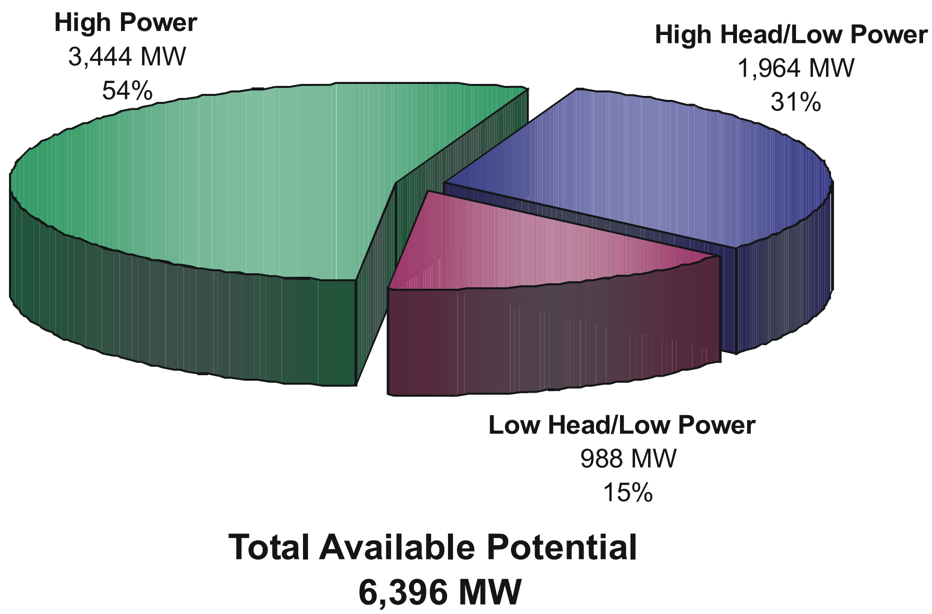


Figure A-7. Distribution of available hydropower potential in the Middle Atlantic Hydrologic Region.

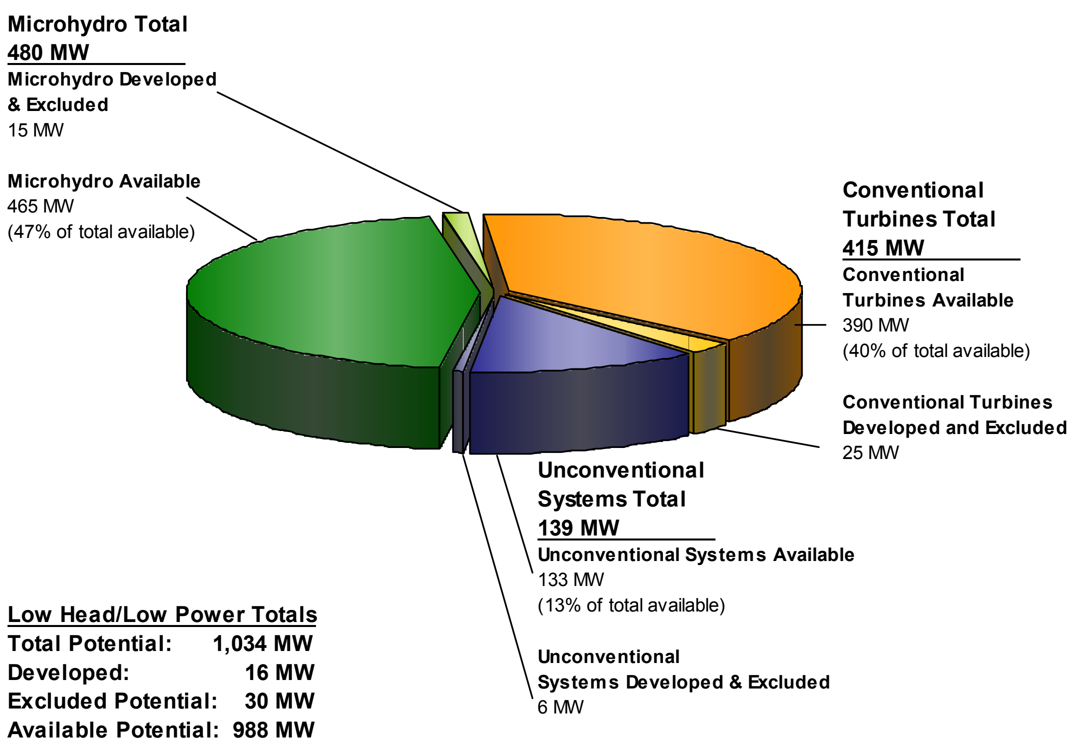


Figure A-8. Distribution of low head/low power hydropower potential in the Middle Atlantic Region among three low head/low power hydropower technology classes.